

# **AVIRIS Radiometric Laboratory Calibration, Inflight Validation, and a Focused Sensitivity Analysis in 1998**

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## **ABSTRACT**

AVIRIS is a calibrated Earth-looking imaging spectrometer that measures the total upwelling spectral radiance in the solar reflected spectrum for 400 to 2500 nm. In 1998 AVIRIS was calibrated in the laboratory using an absolute radiometric calibration standard. To validate the calibration of AVIRIS in the flight environment on board the ER-2 aircraft, an inflight calibration experiment was orchestrated on 15 June 1998. This experiment required field measurement, radiative transfer code calculations, and analysis of AVIRIS spectral data for a calibration target at Rogers Dry Lake, CA. The results of this inflight calibration experiment show that AVIRIS was radiometrically calibrated at better than 96-percent accuracy in 1998. At the time of this experiment, the AVIRIS signal-to-noise ratio was calculated to range from 1000 to 1 in the visible portion of the spectrum and approach 450 to 1 in the 2000-nm spectral region. In addition to the inflight calibration experiment calculations, a focused sensitivity analysis showed that the predicted radiance is most sensitive to the measured surface spectral reflectance and total column water vapor. These measurements, calculations, analyses, and results are presented in this paper.

## **1.0 INTRODUCTION**

NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) measures the total upwelling spectral radiance from 400 to 2500 nm at 10-nm resolution. When flying on board the ER-2 aircraft at 20-km altitude, these radiance spectra are measured as images of 11 by up to 100 km, with 20-m spatial resolution. Spectra from AVIRIS are used for a wide range of science research, application, and calibration objectives (Green et al 1998a). One of the most important characteristics of AVIRIS is the quality of the calibration of the measured spectra. Calibration is required to: (1) enable physically based derivations of parameters from the measured radiance spectra, (2) compare spectra and results from different locations and different times, (3) analyze AVIRIS spectra and compare them with measurements by other instruments, and (4) extract parameters and analyze AVIRIS spectra with computer models. AVIRIS is calibrated in the laboratory before and after the yearly flight season (Chrien et al 1990, Chrien et al 1995, Chrien et al 1996). There are also periodic checks of the laboratory calibration during the AVIRIS flight season. However, all AVIRIS spectral images acquired for investigators are acquired in the airborne environment, not in the laboratory. An inflight calibration experiment strategy has been developed to assess and validate the calibration of AVIRIS in the flight environment. These inflight calibration experiments have been implemented for AVIRIS each year since 1987 (Green et al. 1988, Conel, et al. 1988, Green et al. 1990, Green et al 1991, Green et al. 1992, Green et al. 1993, Green et al. 1995, Green et al 1996, Green et al 1998b). This paper presents the measurements, calculation, analyses, and results of the primary AVIRIS inflight calibration experiment in 1998.

## **2.0 LABORATORY CALIBRATION**

AVIRIS is calibrated in the laboratory with respect to an absolute radiometric calibration standard lamp. The calibration of the lamp is traced to the United States National Institute of Standards and Technology (NIST). For calibration of AVIRIS the lamp is mounted to

illuminate a reflectance panel. The illuminated panel is observed directly by AVIRIS. The total uncertainty is calculated based on uncertainty of the standard lamp, reflectance panel, and transfer repeatability. The radiance of the panel and the calculated uncertainty is given in Figure 1. The ratio of the illuminated panel to the digitized numbers output by AVIRIS gives the radiometric calibration coefficients shown in Figure 2. The process generates the baseline radiometric calibration for AVIRIS.

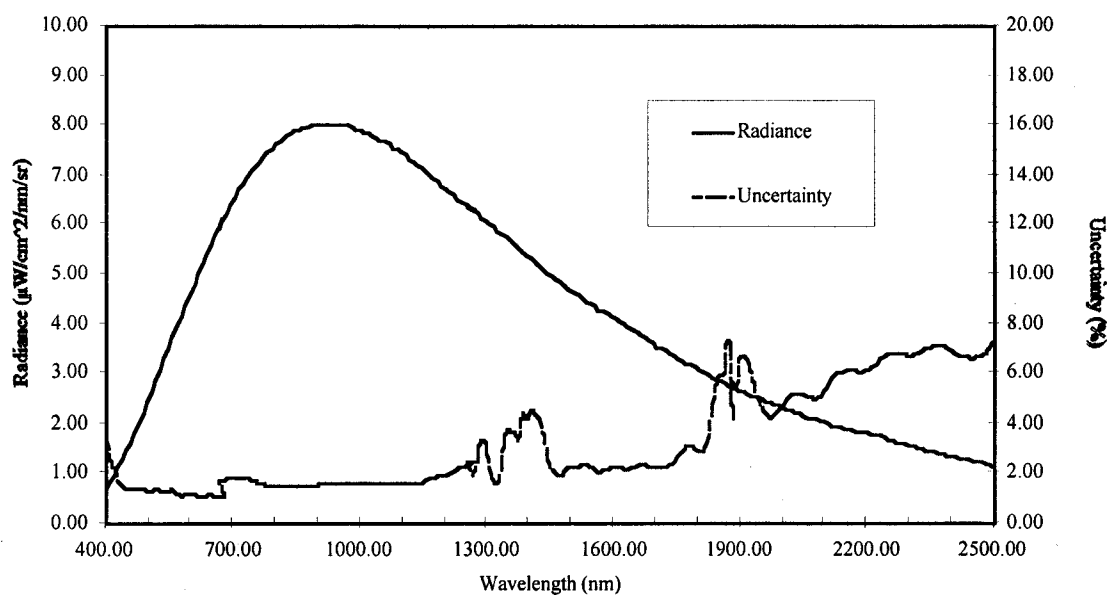


Figure 1. Output of AVIRIS 1998 radiometric calibration standard and calculated uncertainty in percent.

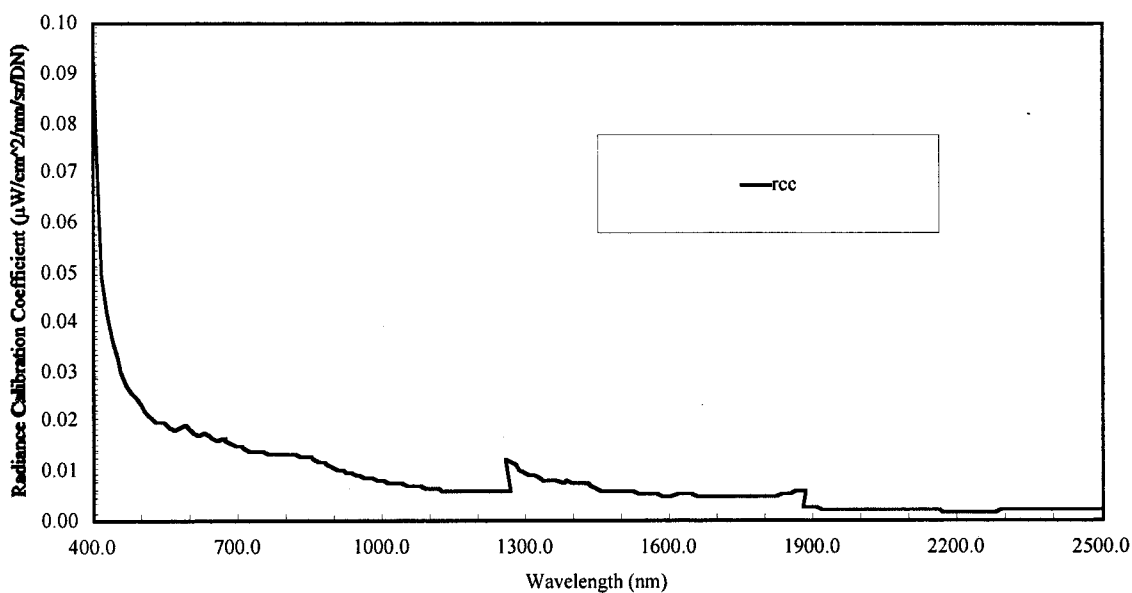


Figure 2. AVIRIS 1998 radiometric calibration coefficients in units of radiance per digitized number.

### 3.0 Field Measurements

A radiative transfer code is used to predict the radiance at the AVIRIS sensor aperture. Field measurements are acquired at a calibration target at the time of the AVIRIS overflight in order to constrain a radiative transfer code. On 15 June 1998 a 40 by 200 m calibration target was established on the surface of Rogers Dry Lake, CA. This area corresponds to an array of 2 by 10 AVIRIS spatial resolution elements. For location of the calibration target, two large blue plastic tarps were placed near each end of the target. The unique spectral signature of these tarps allows exact location of the calibration target in the AVIRIS spectral image data.

The principal field measurement acquired at the calibration target during AVIRIS inflight calibration experiment is the surface spectral reflectance. On 15 June 1998 the surface reflectance of the 40- by 200-m calibration target was measured with a portable field spectrometer with a spectral range from 350 to 2500 nm and spectral sampling of better than 5 nm. More than 250 spectra of the calibration target were measured. Spectra of a reflectance standard were measured periodically during the characterization of the calibration target. The target and standard spectra were then analyzed to generate the reflectance average and uncertainty for the calibration target shown in Figure 3.

In addition to surface spectral reflectance, atmospheric measurements were acquired by a 10-band solar radiometer from near sunrise to past local solar noon. This radiometer was located about 5 km from the calibration target at the Dryden Flight Research Center. The data were analyzed using the Langley method to give the total optical depth of the atmosphere for the 9 continuum bands at the time of the AVIRIS overflight. These optical depths are given in Table 1.

The last in-situ parameter determined was total column atmospheric water vapor. This value was derived from measurements in the 940-nm band of the solar radiometer (Reagan et al 1987, Bruegge et al 1990). A total column amount of 17.35 mm was calculated for this inflight calibration experiment.

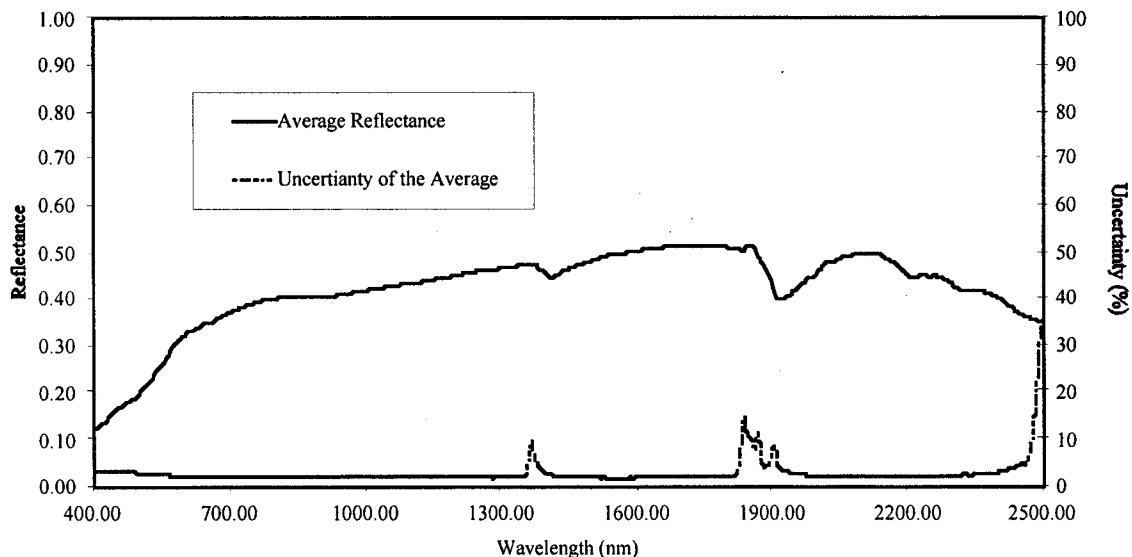


Figure 3. Surface spectral reflectance measured for the calibration target as part of the inflight calibration experiment on 15 June 1998. The reflectance uncertainty for the calibration target average is given as well.

Table 1. Total Optical Depths

Wavelength (nm)	Optical Depth
370	0.6252
400	0.5234
440	0.4018
520	0.2523
620	0.1895
670	0.1273
780	0.0854
870	0.0740
1030	0.0576

#### 4.0 MODEL PREDICTION

The independent prediction of the radiance incident at the aperture of AVIRIS is made using the MODTRAN radiative transfer code (Berk et al 1989). MODTRAN is constrained by the specific time and observation geometry for the AVIRIS image acquisition over the calibration target. In-situ measurements acquired as part of the inflight calibration experiment are used, as are globally acquired measurements of some of the atmospheric parameters. All these parameters are required to accurately predict the radiance arriving at the AVIRIS aperture.

A set of parameters are required that define the observation geometry for this inflight calibration experiment on 15 June 1998. At the time of the measurement of the target AVIRIS was at latitude 34.9935 deg, longitude 117.8349 deg, and 20963 m elevation. The location of the surface calibration target was determined by a global positioning system, and the elevation was derived from a USGS map. The calibration target was located at latitude 34.9935 deg and longitude 117.8345 deg and elevation 709 m. The time of the overflight was 19 hours 31 minutes and 23 seconds GMT.

In addition to time and location, the inflight calibration experiment field measurements are used to constrain the surface and atmospheric characteristics of the MODTRAN model radiance prediction. Optical depths are constrained by selecting a MODTRAN aerosol model and a visibility distance that produces optical depths that closely match the measured optical depths. A 23-km rural aerosol MODTRAN model scaled to 50-km visibility was used for the 15 June 1998 calibration experiment. The corresponding MODTRAN atmospheric optical depths and measured optical depths are shown in Figure 4. The total column water vapor used in the MODTRAN modeled atmosphere was constrained to the amount derived from the solar radiometer 940-nm channel measurements. The measured surface reflectance for the calibration target was used as for the MODTRAN model radiance calculation as well.

Additional parameters that constrain the well-mixed gases were calculated by MODTRAN based on internal climatology tabulations. However, carbon dioxide was adjusted to the

1998 value of 365 ppm and ozone was input based on measurements from the Total Ozone Mapping Spectrometer satellite sensor. A value of 315 dobson units of ozone was used in the 15 June 1998 experiment. With these constraints, the MODTRAN radiative transfer code was run at full spectral resolution to predict the total upwelling spectral radiance incident at the AVIRIS sensor aperture. This predicted spectrum is shown in Figure 5. This spectrum was then convolved to the AVIRIS spectral calibration parameters to give a prediction that is directly comparable to the AVIRIS measured radiance as shown in Figure 6. This independent spectral radiance prediction is the objective of the field measurement and radiative transfer model portion of the inflight calibration experiment.

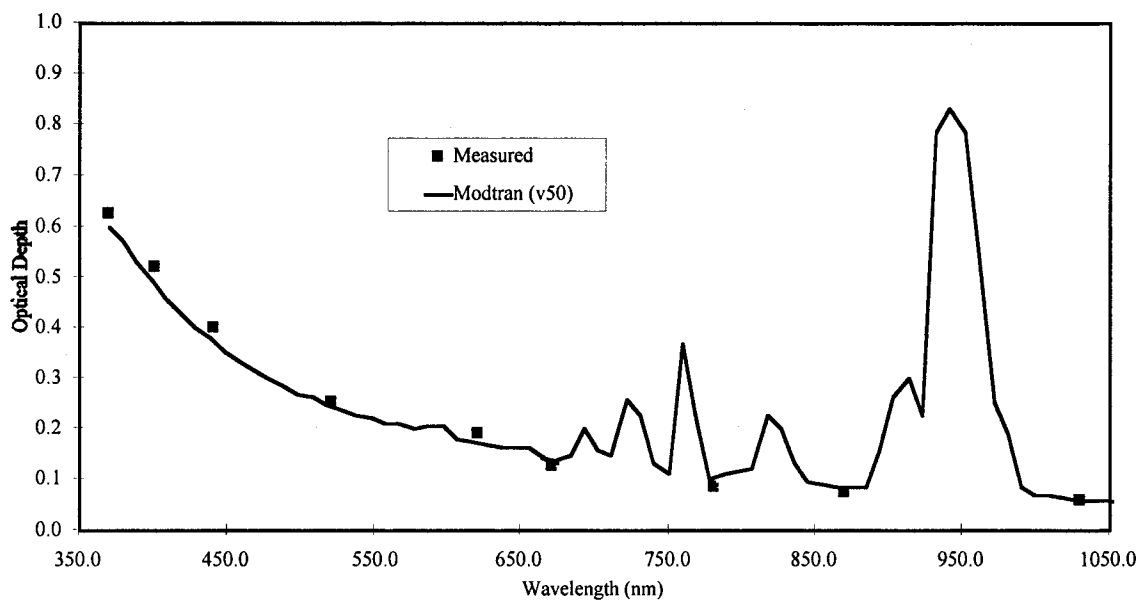


Figure 4. Optical depth plot showing match between in-situ measurements and MODTRAN 23-km aerosol model scaled to 50-km visibility.

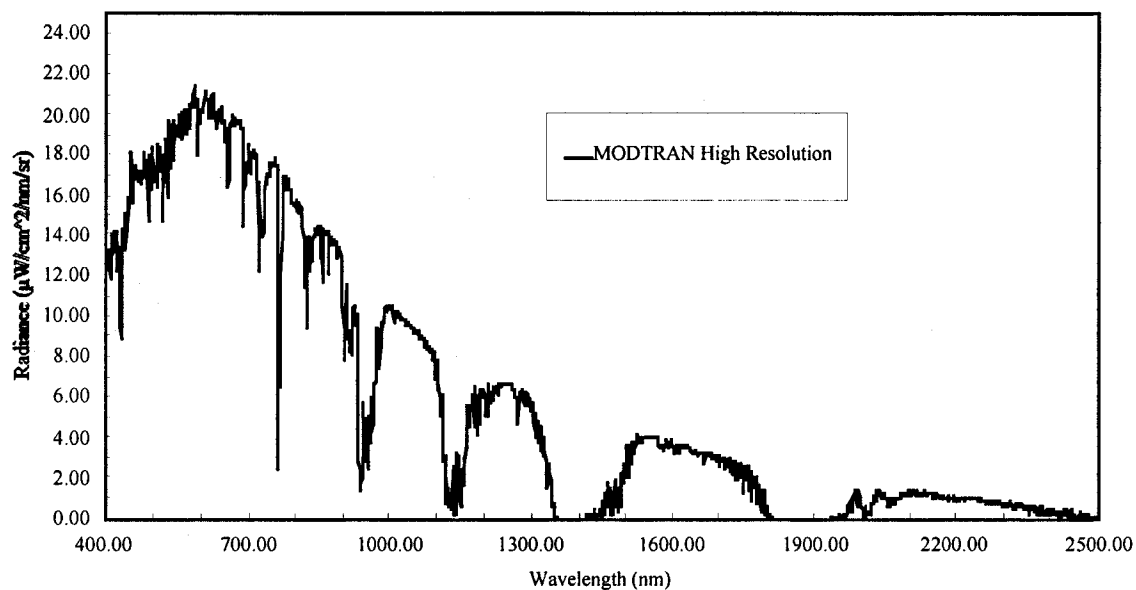


Figure 5. MODTRAN predicted radiance at the AVIRIS aperture for 15 June 1998 constrained by the ephemeris, surface, and atmospheric parameters.

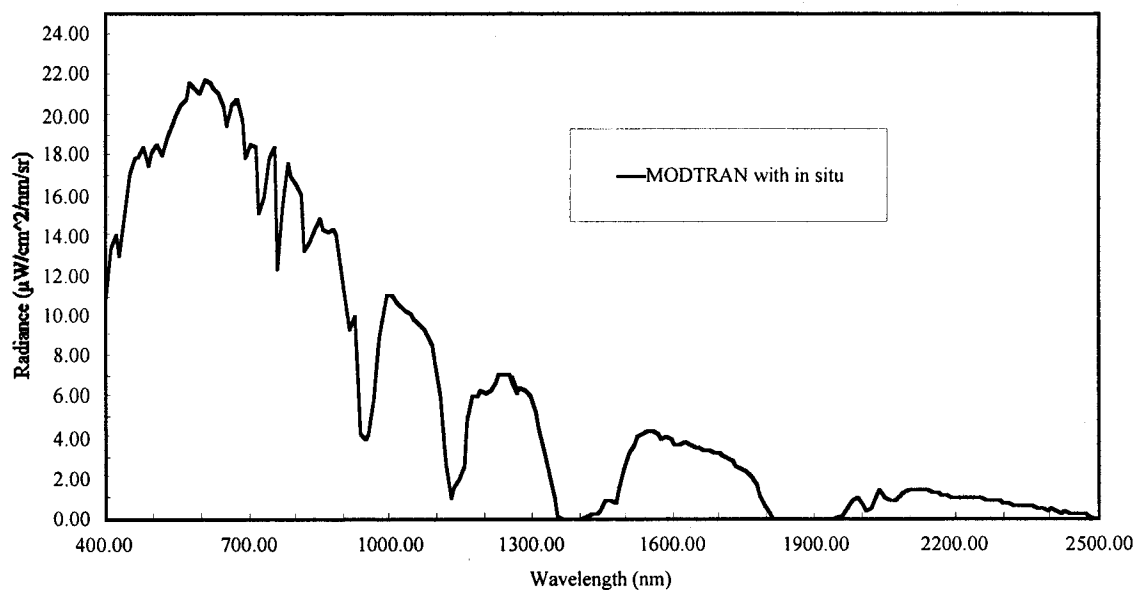


Figure 6. MODTRAN radiance convolved to the 1998 AVIRIS spectral calibration parameters.

#### 4.0 AVIRIS Measurements

AVIRIS acquired spectral image data over Rogers Dry Lake, CA at 19.606 GMT on 15 June 1998. A single channel image from 650 nm wavelength is shown in Figure 7. A simple ratio of the 650 nm channel over 450 nm was used to reveal the location of the blue plastic tarps. The uncalibrated AVIRIS data for the 2 by 10 grid of AVIRIS spatial samples were extracted for the calibration target and is shown in Figure 8. This signal was calibrated to radiance through the AVIRIS calibration data subsystem. The AVIRIS calibration is on the radiometric calibration coefficients, the end-of-scan-line dark signal, and the output of the onboard calibrator. Figure 9 shows the calibrated radiance spectrum. The overall objective of the inflight calibration experiment is to validate this measured radiance from the calibration target and thereby demonstrate that AVIRIS is calibrated in the high-altitude environment of the ER-2 aircraft.



Figure 7. AVIRIS image of Rogers Dry Lake, CA from 655.4 nm in the solar reflected spectrum. The arrow indicates the location of the calibration target on the surface.

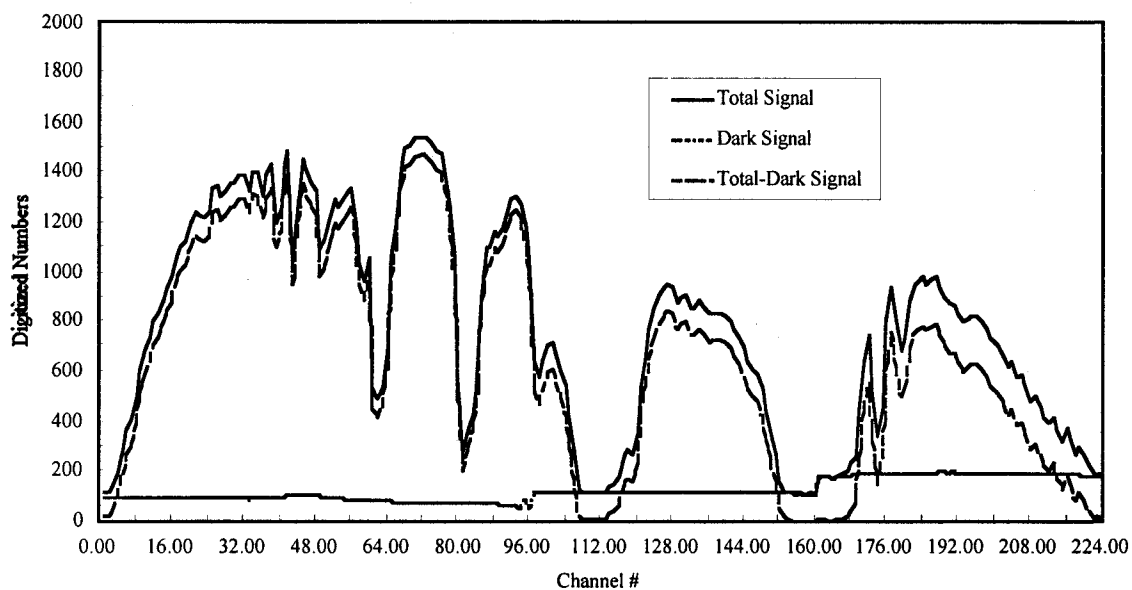
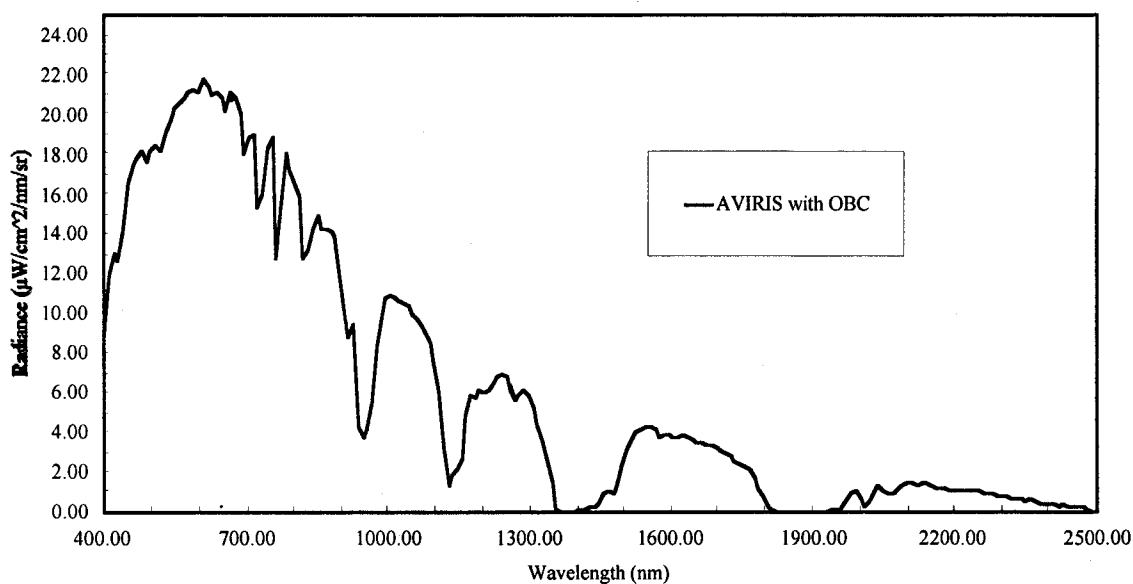


Figure 8. AVIRIS uncalibrated data extracted for the 20 spatial samples of the calibration target at Rogers Dry Lake, CA. The total signal, dark signal, and total minus dark are given.



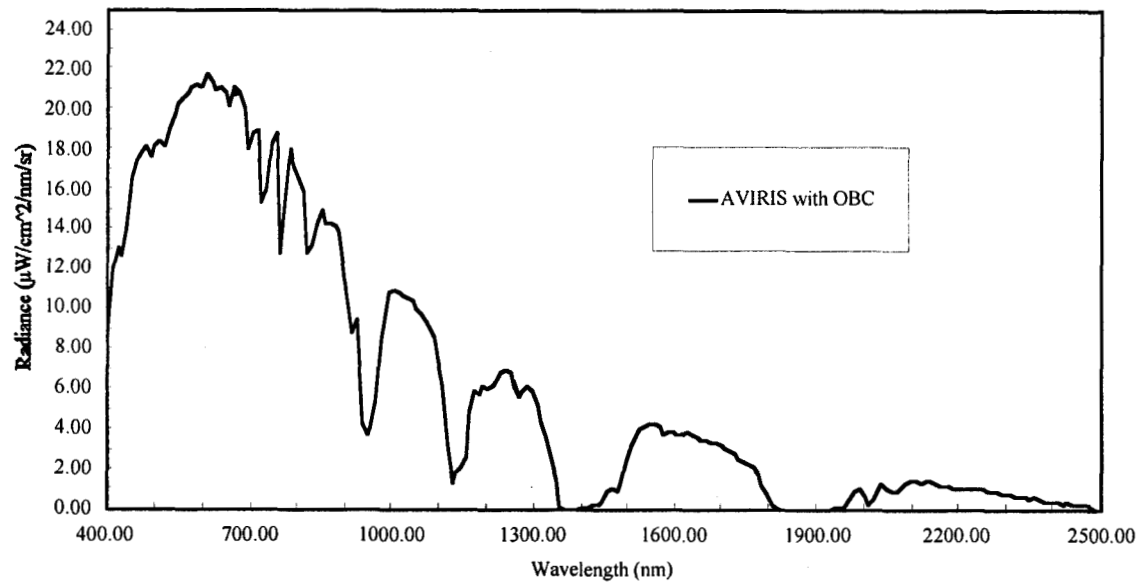


Figure 9. The AVIRIS measured radiance based on the laboratory derived radiometric calibration coefficients and onboard calibrator correction.

## 5.0 RESULTS

This inflight calibration experiment has required the acquisition of field measurements, constraint of the MODTRAN radiative transfer code, and acquisition of the AVIRIS-measured radiance for a specific calibration target. Through analysis of these data a predicted radiance spectrum and the measured radiance spectrum for the calibration target have been generated. Figure 10 shows a comparison of the MODTRAN-predicted with the AVIRIS-measured radiance for the inflight calibration experiment on 15 June 1998. An absolute average agreement of better than 96 percent was achieved across the spectrum. The regions of near complete absorption due to water vapor at 1350 nm, 1900 nm, and 2500 nm were excluded from this calculation. To better understand the residual differences, a ratio of the AVIRIS to the MODTRAN radiance is shown in Figure 11. Areas of disagreement are present near the water vapor bands at 1140 nm, 1350 nm, and 1900 nm. Disagreement is also present at the 1280 nm oxygen band and near the carbon dioxide bands at 2000 nm. In overview the disagreement between the measured and modeled radiance may be grouped into four areas. First, some error exist in the standards used to calibrate AVIRIS. Second, there are errors and uncertainties in the field measurements. Third, errors may be present in the MODTRAN radiative transfer code. Fourth, changes in AVIRIS from the time of laboratory calibration and inflight data measurement introduce some uncertainty. Errors of each types have been found and investigated through analysis of historic AVIRIS inflight calibration experiments stretching back to 1987. This 1998 inflight calibration experiment shows that these sources of error were largely controlled and that AVIRIS was radiometrically calibrated in flight at the 96-percent level of accuracy.

In addition to radiometric accuracy, the radiometric precision of AVIRIS is an important parameter of interest. The radiometric precision may be reported as the signal-to-noise ratio or noise-equivalent delta radiance. The 1998 signal-to-noise ratio of AVIRIS was calculated from AVIRIS measurements of homogeneous targets both in the laboratory and provided by the AVIRIS onboard calibrator. Figure 12 shows the 1998 signal-to-noise ratio was scaled to the AVIRIS reference radiance. The AVIRIS reference radiance was established in 1987 as a basis for comparing AVIRIS performance from year to year. The reference radiance is defined as the radiance from a 0.5 reflectance sea level target illuminated by the Sun with a 23.5-deg solar zenith angle under the 23-km mid latitude summer atmosphere model conditions. Through a series engineering improvements, the signal-to-noise ratio of AVIRIS has improved every year. The dark target noise-equivalent-delta-radiance was also calculated for AVIRIS and is shown in Figure 13. This parameter was calculated as the standard deviation of signal measured with the AVIRIS sensor shutter closed and reported in units of radiance.

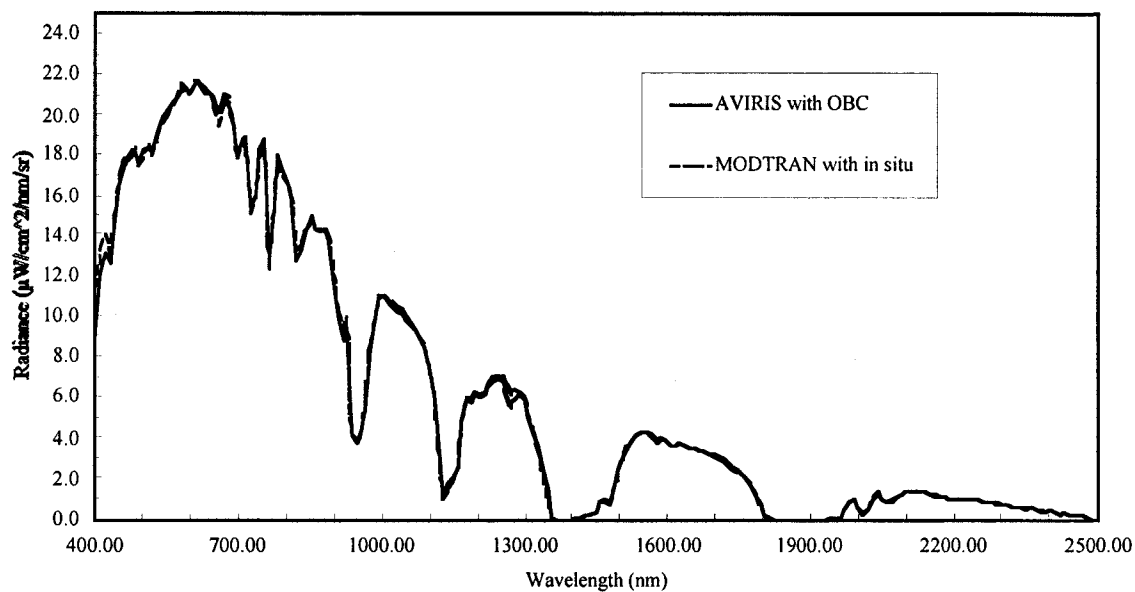


Figure 10. Comparison of the AVIRIS-measured radiance and MODTRAN-predicted radiance for the calibration target at Rogers Dry Lake, CA on 15 June 1998.

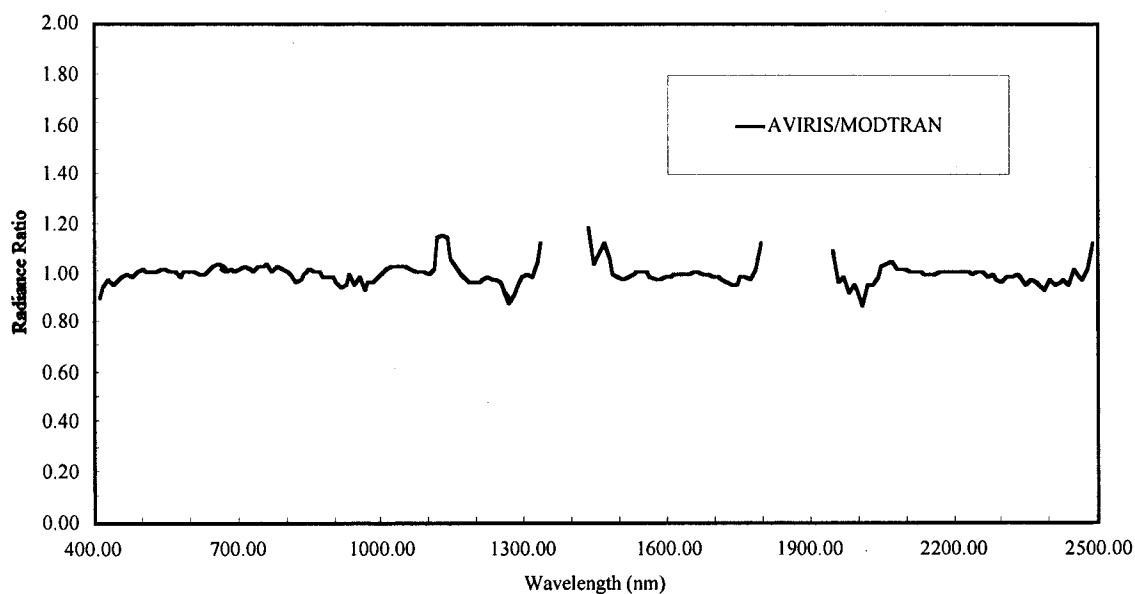


Figure 11. Ratio of the AVIRIS-measured radiance over the MODTRAN-modeled radiance for the inflight calibration experiment of 15 June 1998.

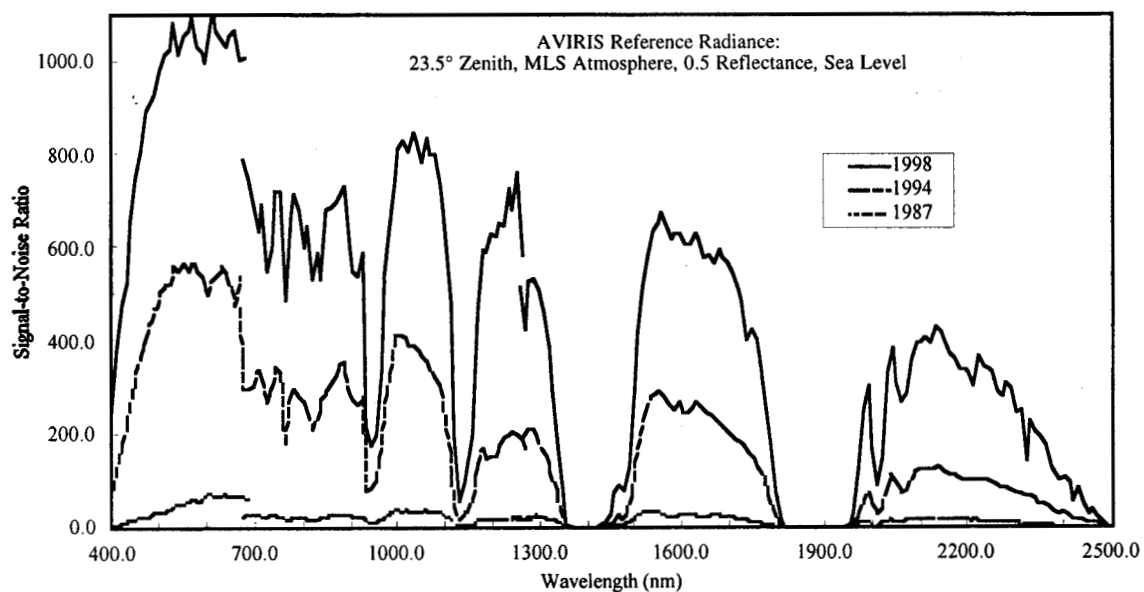


Figure 12. Signal-to-noise ratio determined at the time of the inflight calibration experiment for the AVIRIS reference radiance signal level.

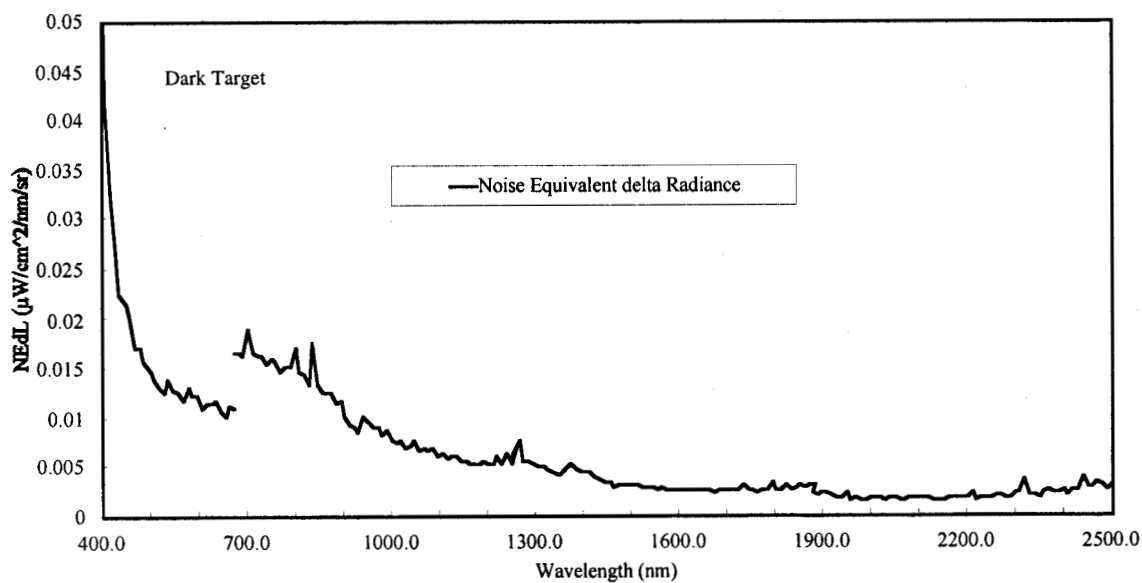


Figure 13. AVIRIS noise-equivalent delta radiance for a dark target on 15 June 1998.

## 6.0 SENSITIVITY ANALYSIS

The inflight calibration experiment is essential to develop confidence in the performance of AVIRIS in the flight environment. This experiment rely heavily on constraint of a radiative transfer code with field measurements. Of interest is the sensitivity of the radiative transfer code output to the constraining parameters. A focused analysis has been performed to assess this sensitivity for the constraining parameters of reflectance, water vapor, and optical depth. This sensitivity analysis was performed for the baseline predicted radiance generated in the 15 June 1998 AVIRIS inflight calibration experiment. The MODTRAN radiative transfer code was then run for three additional cases where errors were introduced in the constraining parameters. MODTRAN was run with a surface spectral reflectance that was in error by +10 percent, water vapor in error by +10 percent, and aerosol model optical depths at 520 nm in error by +10 percent. The percent error in radiance was then calculated with respect to the baseline radiance across the spectrum. Figure 14 show the percent error in radiance for the reflectance, water vapor, and optical depth error cases. This analysis shows that errors in reflectance propagate in a one-for-one manner across almost the entire spectrum. The error in water vapor is also expressed across the spectrum in regions of water vapor absorption. For the relatively clear atmospheres of the inflight calibration experiment, the error in optical depth introduces only a weak error in reflectance. This focused sensitivity analysis shows that inflight calibration experiments, measurement accuracy emphasis should be placed first on reflectance, second on water vapor, and third on optical depth.

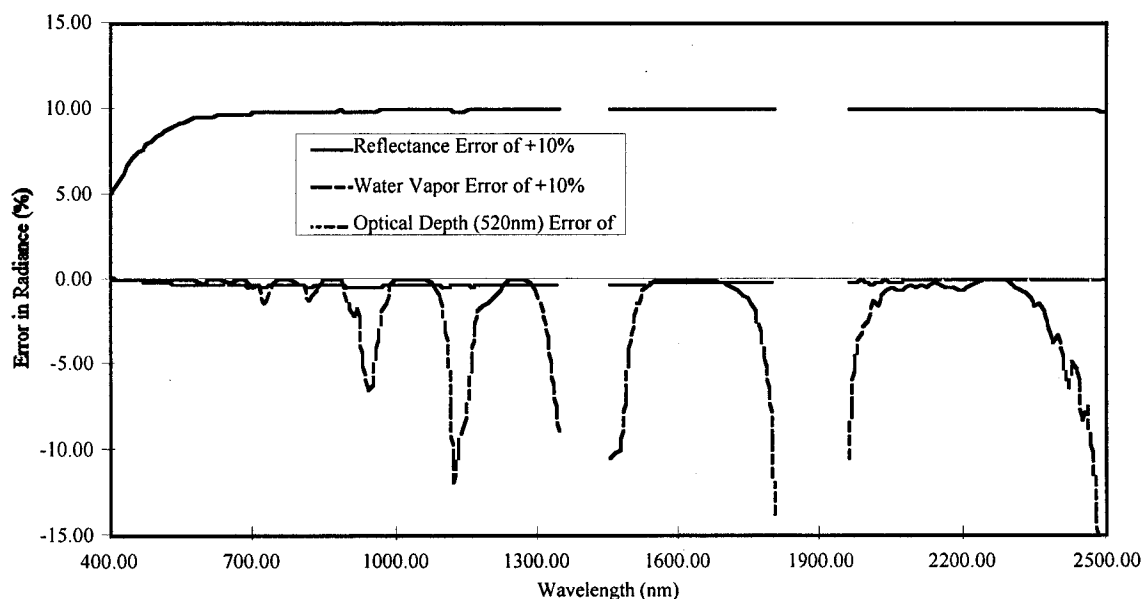


Figure 14. Assessment of the sensitivity of the MODTRAN-predicted radiance for 10-percent errors in constraint of the surface reflectance, the atmospheric optical depths, and the atmospheric water vapor.

## 7.0 CONCLUSION

The measurements, calculations, analyses, and results of the 15 June 1998 AVIRIS inflight calibration experiment have been reported. At the time of the AVIRIS measurement of a

calibration target on Rogers Dry Lake, CA, the surface spectral reflectance, atmospheric optical depths, and atmospheric water vapor properties were measured. The measured parameters, along with knowledge of the time and location of the measurements, were used to constrain the MODTRAN radiative transfer code and predict the radiance incident at AVIRIS. Global measurements of ozone and carbon dioxide were also used to more accurately constrain MODTRAN. The measured AVIRIS data were extracted for the calibration target and calibrated to the incident total upwelling spectral radiance. Comparison of the predicted and measured radiance shows that AVIRIS was calibrated at better than the 96-percent level on average across the spectrum. In some portions of the spectrum, the calibration was shown to be better than 96 percent, and in others worse than 96 percent. Some of the larger disagreements were shown to occur near the spectral absorption regions of atmospheric gases. The inflight signal-to-noise ratio of AVIRIS and the dark-target, noise-equivalent delta radiance were calculated and reported as part of the 15 June 1998 inflight calibration experiment. In addition to reporting the results of the inflight calibration experiment, a focused sensitivity analysis was performed to show the sensitivity of the radiative-transfer-predicted radiance to the constraining field measurements. The predicted radiance was found to be most sensitive to the accuracy of the measured spectral reflectance of the calibration target, and to the measured total column of water vapor. Less sensitivity was shown for the measurement of the optical depth under the clear-sky condition of the inflight calibration experiment. Inflight calibration experiments are essential to understand the performance of imaging spectrometers in the flight environment where data for science research and applications are measured. Research and analysis must continue to further assess the dependencies and improve the quality of these experiments.

## 8.0 References

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